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Prototyping Capacitive Sensing Applications with **OpenCapSense**

OpenCapSense is a prototyping platform to develop innovative applications that rely on perceiving humans with electric fields. Despite today's use of capacitive sensing mostly as a method to detect touch, it offers many interesting facets that range from mid-air interaction to contactless indoor localization and identification. The platform provides active sensors to detect human interactions at distances of more than 40 cm, by generating electric fields. Passive sensors allow for measuring changes in electric fields that occur naturally in the environment, enabling detection distances up to 2 m.

Photo, istockphoto.com

While humans are not able to perceive weak electric fields with their senses, animals like electric fish or platypuses have the ability to sense and even generate them. The principle of electroreception is mostly used in saltwater environments due to its high conductivity. This enables many species to locate their prey or even communicate with others of their kind [2].

Compared to the millions of years that animals have actively used electric field sensing, human exploitation only dates back about a century. One of the first known uses in 1907 is the string galvanometer, which captures the compression of a beating frog heart between two capacitor plates [1]. A more prominent example, still in use today, is a music instrument invented in 1919 by the Russian physicist Leon Theremin [4]. The instrument, named after Theremin himself, consists of two conductive poles, called electrodes, in which a generated electric field is modified by hands at distances up to 50 cm. Changing the proximity to either electrode results in a change of pitch or volume.

Both devices are examples for active capacitive sensing. The most widely employed active methods are found in capacitive touch screens or non-mechanical buttons that react on touches of a finger. However, electric fields are not only affected by these very local interactions. Passive capacitive sensing can achieve distances of several meters, for example, by monitoring electric potential changes in human bodies. To enable experimentation with electric field sensing at all interaction distances and with a high flexibility in sensing methods, we developed OpenCapSense – a versatile platform to prototype capacitive sensing applications [8]. It supports passive and active sensing methods, including both self-capacitance measurements with single electrodes and mutual-capacitance measurements between two or more electrodes. The electrodes can be arbitrarily shaped and made from many materials, including wires, transparent conductors, plate electrodes, or conductive thread. OpenCapSense is open source. The users can work with raw sensor data over the serial interface, or modify parameters including measurement time and filters on the chip.

PERCEPTION WITH ELECTRIC FIELDS

In general, OpenCapSense can be used for both active and passive capacitive sensing. Passive capacitive approaches sense electric fields emitted by other objects (e.g., power lines or humans while walking), while active capacitive methods emit an electric field and measure its properties.

Active Capacitive Sensing

Nowadays, most methods to sense proximity to human body parts, e.g., for sensing human touch, use active capacitive sensing. In this field, three operating modes can be distinguished which are shown in Figure 1 [3]. OpenCapSense is able to cover these active modes with two sensor types – one used for loading mode measurements, and one for shunt and transmit mode sensing.

Applying loading mode, or in other terms self-capacitance measurements, just requires a single electrode that conducts the measurement. This makes loading mode sensors very easy to deploy, with the additional benefit of being easily shield-able. Shielding may be required for many

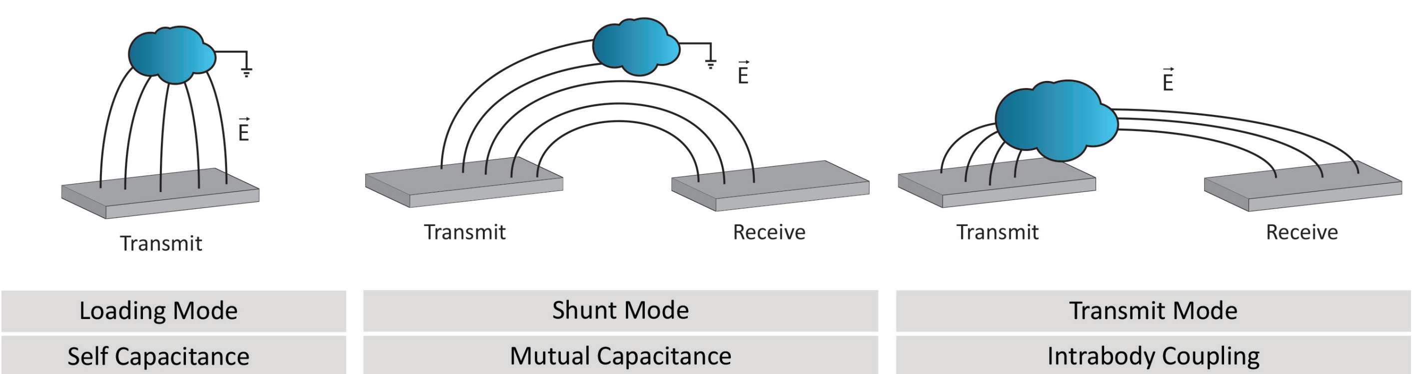

FIGURE 1. Smith et al. distinguish between three different active electric field sensing operating modes [3].

reasons, most importantly to avoid electromagnetic interference from appliances like switch-mode power supplies. Also, the sensitivity of a sensor can be raised by using OpenCapSense's active shielding approach that reduces parasitic capacitance, for example, to grounded objects that are close to the electrode. Moreover, using larger electrodes, e.g. 100 cm², allows for achieving sensing distances of 40 cm with good spatial resolution [8].

In shunt mode, an object disturbs the electric field between two electrodes and essentially reduces the capacitance between them. Transmit mode is entered when the object is very close to the transmit electrode. This results in an increase of capacitance, as the object takes over the electric potential of the transmit electrode and thus becomes an electrode itself. A shunt and transmit mode sensor requires at least one transmit and one receive electrode. This mode also enables conducting measurements between multiple transmitters and receivers, resulting in *N=transmitters·receivers* measurements. This concept is widely used in capacitive touch screens to achieve a high spatial resolution, where the capacitance in the intersection between two orthogonal electrodes is measured.

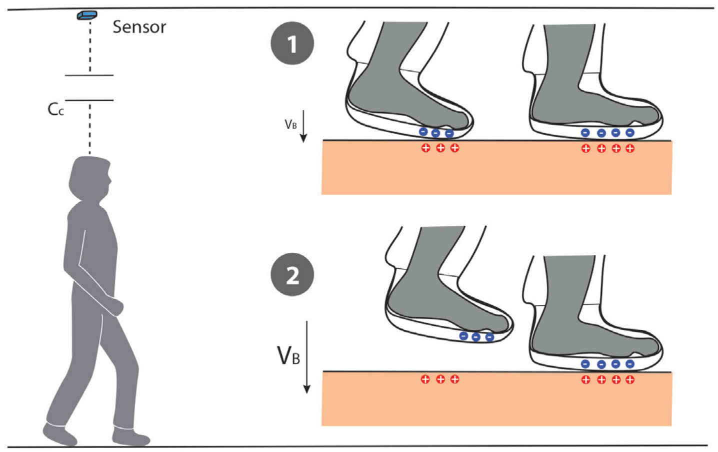

FIGURE 2. Due to contact charging and the triboelectric effect, the human body itself generates significant electric fields that can be perceived by passive capacitive sensors.

Passive Capacitive Sensing

A recent addition to OpenCapSense allows for passively sensing electric fields in the environment [13]. These electric fields occur through various ways, for example, being emitted by power lines or electric devices. Also, humans generate significant electric fields. During walking, a human accumulates and loses electrical charge due to contact charging, friction, and simple discharges. Combined with a change in capacitive coupling to the environment, e.g., while lifting a foot, this results in a change in body voltage as shown in Figure 2.

Nowadays, passive capacitive sensing is mostly applied to monitor electric potentials on the body, for example to measure ECGs or EMGs. Sensing interactions with the environment is still an ongoing research topic and seldom employed in commercial products.

Electrode Materials

A capacitive sensor relies on an electrode, which is used to build up an electric field to an object nearby. In most active systems, increasing the electrode size also enables the detection of farther objects. In passive systems, larger electrodes induce higher noise, which can reduce the system's sensitivity. Typical sizes of area electrodes range from 0.5 x 0.5 cm to 20 x 20 cm [6]. For wire electrodes, we achieve reasonable performances at lengths ranging from a few centimetres up to several metres.

Electrodes can be composed of various conductive materials, with copper among the most prominent examples. As only very small displacement currents are flowing back and forth (usually in the region of a few pA), materials with lower conductivity (see Figure 3) open the space to new applications. Transparent electrodes can be deployed on windows or as an overlay to displays. Flexible electrodes open new possibilities in interactive garments, for example, to realize beds that recognize the posture of immobilized people [12]. In other works, everyday conductive objects like door knobs are used as the sensing electrode [7].

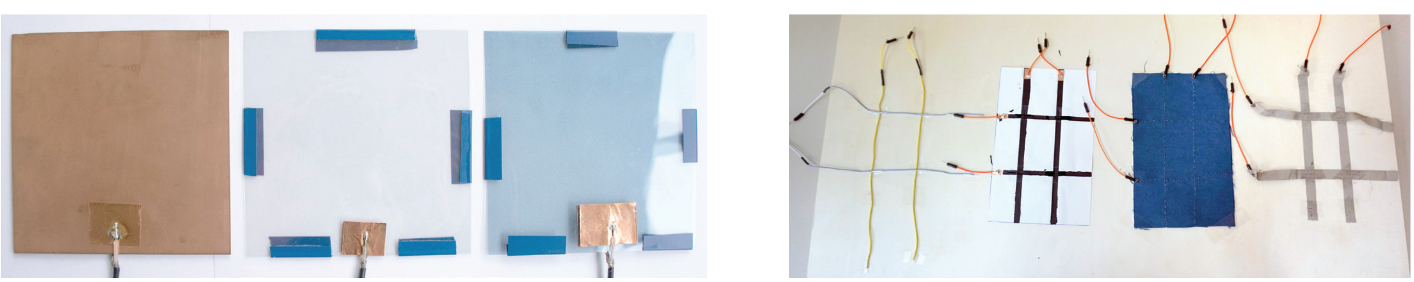

FIGURE 3. Different electrode materials for prototyping. From left to right: copper plate; PET sheet with indium-tin-oxide; PET sheet with PEDOT:PSS; copper wires, conductive paint on fabric, conductive yarn, conductive fabric as presented in [12].

OpenCapSense ARCHITECTURE

Since the 1990s several research teams have been working on capacitive proximity sensing. The MIT Media Lab developed hardware systems for electric field imaging and released hardware sketches and algorithms [3]. The CapToolKit developed by Wimmer et al. was even more accessible with open hardware and firmware that could be ordered online [5]. It could interface eight capacitive proximity sensors and arbitrary electrodes, before transmitting the measurements using a USB-to-Serial interface. There are several shortcomings that we identified, while extensively using it for prototyping from 2009 to 2013. The platform only supported a single sensor type, had a low-powered 8-bit microcontroller and was not able to interface multiple boards. We collaborated with Raphael Wimmer in creating the successor OpenCapSense, which overcomes these limitations and improves on the resolution of the capacitive measurements. The schematics, board layouts, and software can be downloaded on our website www.opencapsense.org. Researchers also have the opportunity to order OpenCapSense boards and sensors. Both hardware and firmware are open-source. We have included modification of measurement periods, filters, or multiplexing methods in post-processing in the firmware. If the users desire, they can turn off any processing and work with raw sensor data over the serial interface.

The system, as shown in Figure 4, consists of the OpenCapSense board and OpenCapSense sensors that are connected to electrodes. The OpenCapSense board is built around a 32-bit Texas Instruments C2000 microcontroller. It is the interface for up to eight sensors, handles USB-to-serial communication with a connected PC, and provides two additional interfaces. The I2C interface is suited for connecting additional sensors, such as accelerometers. The CAN interface is primarily used for combing multiple OpenCapSense boards and sending synchronization signals and data. On our website, application developers can find examples in Java or Python, for example, to build a custom Theremin with OpenCapSense.

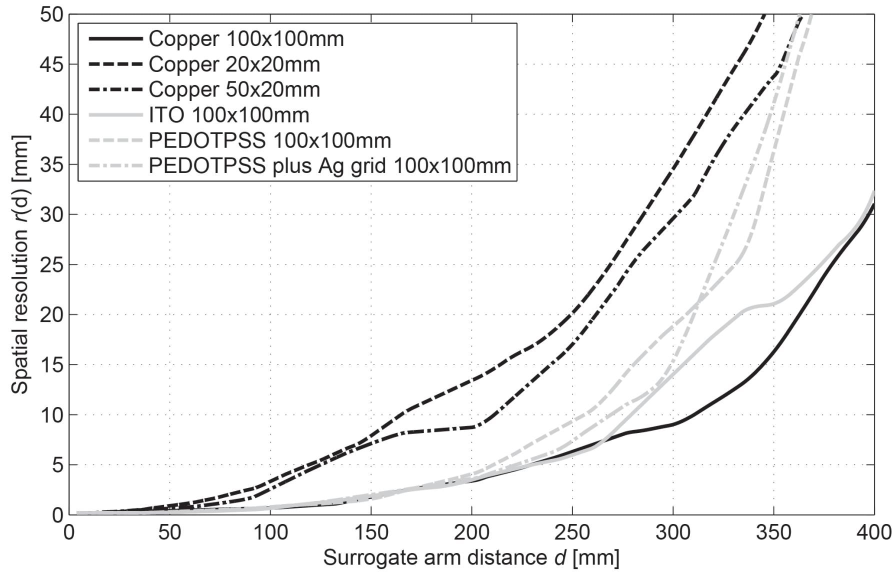

FIGURE 5. OpenCapSense's resolution for active loading-mode measurements tested with a surrogate arm (pipe) for varying materials and electrode sizes at different distances [8].

OpenCapSense can provide up to 1000 samples per second, which enables high-speed applications like recognizing humans tripping and falling [8]. For slower update rates of 160 samples, a sensor resolution up to 1 fF is achievable. This maps to sub-mm accuracy for hand movements at distances of 10 cm. We have tested OpenCapSense with a surrogate arm consisting of a grounded piece of pipe with several electrode materials and sizes at different distances. The resulting spatial resolutions of active loading mode measurements are shown in Figure 5. The spatial resolution indicates the certainty of an object at the present distance and is calculated from repeated measurements and the determined standard deviation. The materials were copper, ITO (indium tin oxide) – a transparent conducting oxide, and PEDOT:PSS – a transparent conducting polymer. All materials and sizes perform well, with larger electrodes and more solid materials performing better at larger distances. However, one major challenge with capacitive sensing is that initial assumptions must be posed on the size and type of detectable objects. This may result in the outcome that a large hand appears closer than a small one [9].

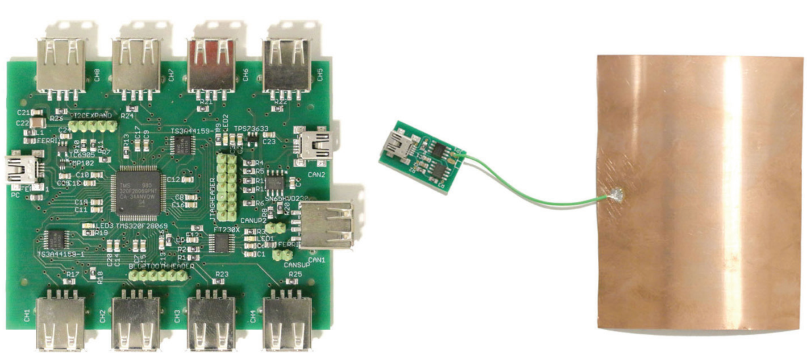

FIGURE 4. OpenCapSense consists of a controller board (left) comprising up to eight sensors (middle) with conductive electrodes (right) that are used to perceive electric fields.

PROTOTYPING EXAMPLES

In the following, we will present two recent prototyping examples – one using active capacitive sensing and one that passively monitors ambient electric fields.

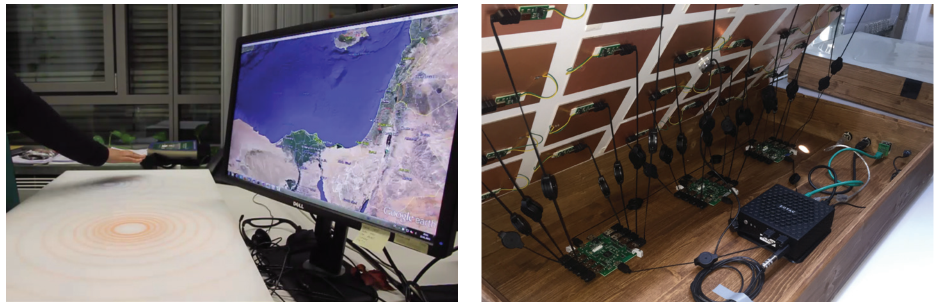

FIGURE 6. Controlling Google Maps with CapTap (left) and internal view of prototype (right).

FIGURE 7. OpenCapSense using passive capacitive sensors deployed on a ceiling for indoor localization and identification (right). The system supports different floor materials like bare concrete (left), wooden flooring, or carpets.

Active Capacitive Gesture Recognition

Gesture recognition is a common use case for capacitive sensors, as evidenced by ubiquitous use in touchscreens. Using capacitive proximity sensors extends the range from touch to mid-air gesture interaction at a distance of up to 40 cm [8]. CapTap [14] is a large-area interaction device is a large-area interaction device based on capacitive proximity sensors that supports both touch interaction (supported by acoustic touch detection [10]) and gesture tracking at distances up to 30 cm (see Figure 6, left). This extended interaction space supports various interaction layers, e.g., for rapidly searching through large data sets. Another application is interaction for users with motor deficiencies, as it can be configured for control with coarse gestures.

As the table has a size of 80 x 50 cm, we need a larger number of electrodes to achieve a good spatial resolution. OpenCapSense provides two major advantages in this scenario. First, using two-sided copper plates with active shielding prevents the electrodes from picking up noise produced by a mini-PC located underneath them (Figure 6, right). The second advantage is provided by the CAN interface that allows us to link together several boards and synchronize their measurement. CapTap uses 24 loading mode sensors that are connected to three OpenCapSense boards. As adjacent sensors can disturb the measurement process of one another, we synchronize the boards, so they measure capacitance in succession.

The electrode layout is a regular 6x4 array, as shown in Figure 6 on the right. This has similarities to CCD or CMOS sensors, installed in digital cameras. Even though the resolution is much smaller and there is no equivalent to optical lenses, this inspired us to use computer vision methods for object tracking. The capacitance value of the sensor readings is used to create a capacitive image with 24 pixels. We use scaling and blob detection methods to track the position and elevation of one or two hands above the table. It is also possible to infer further information about the tracked objects, e.g., the center of the palm of the hand or the angle of the arm relative to CapTap.

OpenCapSense IS UNIQUE IN THE WAY THAT IT ALLOWS FOR LARGE-SCALE DEPLOYMENTS (E.G., COUCHES, FLOOR SURFACES, AND CEILINGS) WITH THE USE OF DIFFERENT SENSING METHODS. BUT MOST IMPORTANTLY, WE PROVIDE A FULLY TRANSPARENT OPEN-SOURCE HARDWARE AND SOFTWARE IMPLEMENTATION

Passive Capacitive Indoor Localization and Identification

Infrastructure-based indoor localization systems are needed in applications like health care or home automation. Although approaches based on video cameras have the upper hand in terms of accuracy and maturity, they raise privacy concerns and require heavy computation. This motivated us to investigate a new way of perceiving human beings, monitoring the electric fields caused due to human motion [13].

As described in the previous section, a human being naturally generates an electric field when walking. This field carries an ambiguous and nonlinear information about the person's position. To monitor this field, we deployed OpenCapSense with six passive electric field sensors on the ceiling of a room, shown in Figure 7. These sensors build up two grid cells with a total size of 2.5 x 2 m.

We first merge all sensor readings in a common model, which enables us to localize a person with a very similar technique like trilateration. In our use-case, we reach an overall localization accuracy of 0.16 m for normal walking and 0.13 m for slow walking. Based on the position, we reconstruct the change in body electric potential of the person, as if it was measured with a direct contact-based instrument. As the body electric potential changes are very characteristic for a person, we are able to identify multiple people based on their electric potential footprint. In the shown experiment, we reached an accuracy of 94% for 4 users, and 75% for 30 users. Although these unique footprints can be retained over multiple days, they change when the user changes shoes.

OpenCapSense enabled us to efficiently prototype the scenario, as the micro-controller allows for a significant amount of digital signal processing, e.g., to filter powerline noise or generate Fast-Fourier-Transforms in real-time. Additionally, it is easy to distribute sensors over a larger area using cheap and easily obtainable USB connector cables.

DISCUSSION & OUTLOOK

Our platform reduces the barrier to prototype capacitive sensing applications in many ways. OpenCapSense is unique in the way that it allows for large-scale deployments (e.g., couches, floor surfaces, and ceilings) with the use of different sensing methods. But most importantly, we provide a fully transparent open-source hardware and software implementation. In contrast, many commercial solutions apply black-box filtering mechanisms that often compensate for the effects researchers aim to measure. This also gives researchers the opportunity to customize the boards and firmware to incorporate their own design requirements.

OpenCapSense consolidates the fragmented landscape of capacitive sensing solutions by providing a single platform to explore multiple differentiated sensing methods. Considering active capacitive sensing, we are able to reach interaction distances more than 40 cm [8]. This enables new ways of mid-air gesture sensing or activity recognition in furniture. With passive sensing, we are able to perceive electric fields at greater distances of up to 2 m [13]. Especially, the contactless monitoring of the electric potential of a human body opens new ways to recognize human activities; for example, when people operate devices, interact with furniture or walk around.

As our human senses are not able to perceive electric fields, it is often hard to imagine where research and industry in this field are heading. However, our work shows that capacitive sensing can be used for significantly more applications in human perception than the omnipresent touch sensing. Compared to capacitive sensing research, industry demands for high reliability and the ability to work under every condition, e.g., when a phone is recharging from a switch-mode power supply. Commercial examples like capacitive hover and touch on smartphones [11] show that extensive signal processing and a carefully designed sensing setup can lead to innovative, robust and highly interactive user experiences. ■

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REFERENCES

[1] Barold, S.S. Willem Einthoven and the Birth of Clinical Electrocardiography a Hundred Years Ago. *Cardiac Electrophysiology Review 7*, 1, 99–104.

[2] Heiligenberg, W. *Principles of Electrolocation and Jamming Avoidance in Electric Fish: A Neuroethological Approach*. Springer-Verlag, 1977.

[3] Smith, J.R.: Electric Field Imaging. Phd Thesis. Massachusetts Institute of Technology, 1999.

[4] Glinsky, A. *Theremin: Ether music and espionage*. University of Illinois Press, 2000.

[5] Wimmer, R., Kranz, M., Boring, S., and Schmidt, A. A capacitive sensing toolkit for pervasive activity detection and recognition. *Proceedings - Fifth Annual IEEE International Conference on Pervasive Computing and Communications, PerCom 2007*, (2006), 171–180.

[6] Grosse-Puppendahl, T., Marinc, A., and Braun, A. Classification of User Postures with Capacitive Proximity Sensors in AAL-Environments. *Proceedings AmI International*, (2011), 314–323.

[7] Sato, M., Poupyrev, I., and Harrison, C. Touché: enhancing touch interaction on humans, screens, liquids, and everyday objects. *Proceedings CHI*, (2012), 483–492.

[8] Grosse-Puppendahl, T., Berghoefer, Y., Braun, A., Wimmer, R., and Kuijper, A. OpenCapSense: A rapid prototyping toolkit for pervasive interaction using capacitive sensing. *2013 IEEE International Conference on Pervasive Computing and Communications, PerCom 2013*, (2013), 152–159.

[9] Grosse-Puppendahl, T., Braun, A., Kamieth, F., and Kuijper, A. Swiss-cheese extended: an object recognition method for ubiquitous interfaces based on capacitive proximity sensing. *Proceedings CHI*, (2013), 1401–1410.

[10] Braun, A., Krepp, S., and Kuijper, A. Acoustic Tracking of Hand Activities on Surfaces. *Proceedings of the 2nd International Workshop on Sensor-based Activity Recognition and Interaction*, ACM (2015), 9:1–9:5.

[11] Microchip Inc. MGC3130 3D Tracking and Gesture Controller. 2015.

[12] Rus, S., Sahbaz, M., Braun, A., and Kuijper, A. Design Factors for Flexible Capacitive Sensors in Ambient Intelligence. In *Ambient Intelligence*. Springer, 2015, 77–92.

[13] Grosse-Puppendahl, T., Dellangnol, X., Hatzfeld, C., et al. Platypus — Indoor Localization and Identification through Sensing Electric Potential Changes in Human Bodies. *Proceedings of the 14th ACM International Conference on Mobile Systems, Applications and Services (MobiSys)*, (2016).

[14] Andreas Braun, Sebastian Zander-Walz, Stefan Krepp, Silvia Rus, Reiner Wichert, and Arjan Kuijper. 2016. CapTap: combining capacitive gesture recognition and acoustic touch detection. In *Proceedings of the 3rd International Workshop on Sensor-based Activity Recognition and Interaction* (iWOAR '16). ACM.